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KRISTIAN HERTZ

SIMPLE TEMPERATURE CALCULATIONS OF FIRE EXPOSED CONCRETE CONTRUCTIONS

Den polytekniske Læreanstalt, Danmarks tekniske Højskole

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CONTENTS

Joseph Fourier

PREFACE

Joseph Fourier wrote the comprehensive treatise: "Théorie du Mouvement de la Chaleur dans les Corps Solides" [3] only a few years after his return from Egypt, where he had participated in the campaign of Napoleon Bonaparte in 1799.

The work has been a valuable part of the natural philosophy ever since and a direct source of inspiration for scientists as J.C. Maxwell and Lord Kelvin.

Especially the following theorem has become of outstanding importance to fire technology: "Suppose the different points of a homogeneous solid of any form whatever, to have received initial temperatures which vary successively by the effect of the mutual action of the molecules, and suppose the equation $v = f(x,y,z,t)$ to represent the successive states of the solid, it may now be shown that v a function of four variables necessarily satisfies the equation

$$\frac{dv}{dt} = \frac{K}{CD}\left(\frac{d^2v}{dx^2} + \frac{d^2v}{dy^2} + \frac{d^2v}{dz^2}\right) ."$$

This report deals with solutions to the equation.

Copenhagen, June 1981
Kristian Hertz
M.Sc. Ph.D. Struct. Eng.

SUMMARY

The problem of determining the temperature di
bution in fire exposed concrete constructions
analysed.

Based on the knowledge of the thermal propert
concrete the accuracy of a calculational proc
is estimated leading to the conclusion, that
application of simple approximative solutions
well justified.

Some simple exact solutions to Fouriers equat
presented, and a new procedure is developed c
bing the temperature distribution in a rectan
concrete specimen exposed to a realistic fire
standard fire course extended with a decay pe

In four appendices the method is formulated
pocket calculator program and a fast EDP sub
and examples of calculated distributions are
with results of more complicated calculations
measurements from fire tests.

ACKNOWLEDGEMENTS

I would like to express my gratitude to senic
turer T. Jakobsen for reading the manuscript
staff of the Institute of Building Design for
and printing the report.

SYMBOLS

a_1	constant
a	thermal diffusivity
C	heat capacity as used by Fourier
C_i	constants
C'	half period
c_p	specific capacity of heat
D	density as used by Fourier
D'	thermal amplitude
E'	constant temperature
f_i	functions
i_v	enthalpy
K	thermal conductivity
L	constant
m	constant
r	radius
T	temperature
t	time
v	angular velocity
v	temperature as used by Fourier
x	coordinate
y	coordinate
z	coordinate
ξ_{Tx}	temperature reduction in the depth x
ρ	density

INTRODUCTION

A precondition for an analytical determination of the fire resistance of a construction is the abil: of using a calculational approach for estimating · temperature distribution through the loadbearing I of it.

While the laws of statics remain unchanged the pr(perties of the materials are sensitive to the tem· perature development.

The temperature is the key parameter, and its var· riation as a function of time and place is especia important for the understanding of the function oi fire exposed concrete structures, because large thermal differences normally occur, giving rise tc internal stresses and a lack of simultaneity which is often ignored without any reason.

In an age of electronic data processing the standa answer to complicated questions is calculational power. Nevertheless simple procedures are still ju fied in order to achieve reasonable solutions quic and at small efforts.

The need for procedures of this kind for calculati of temperatures in fire exposed constructions is i creasing because still more constructions has to b designed for resistance to fire.

This is the case especially if the thermal propert which are used in the calculations are so poorly d termined, that a greater accuracy of the procedure is meaningless.

ON THE THERMAL CONDUCTIVITY OF CONCRETE

The sort of aggregate used is highly decisive for the value of the thermal conductivity and its variation with the temperature.

The water-cement ratio, and dependent on this, the porosity is also of major importance.

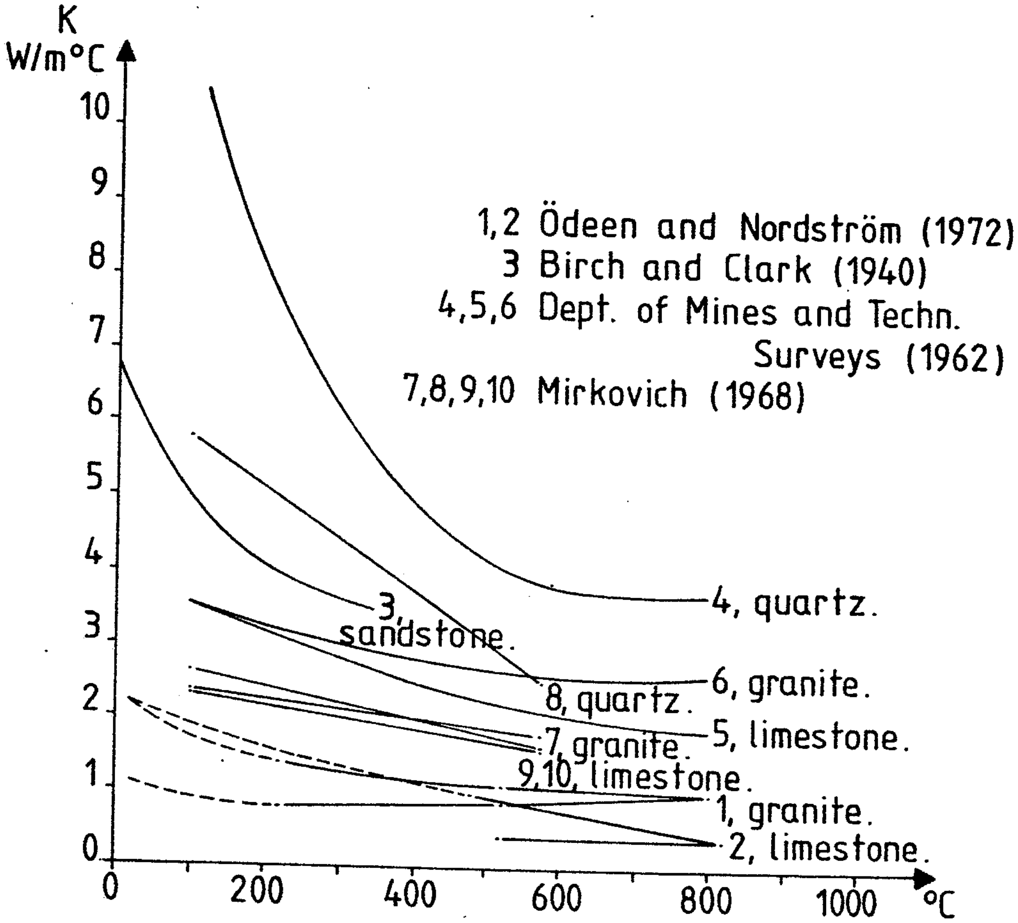
It is therefore obvious that if the thermal conductivity is not measured for the actual concete the assessment of this value can give rise to considerable deviations when calculating a temperature distribution.

If the value is measured as a function of the temperature, the conditions under which such a measurement is performed are much different from the conditions being found in a construction exposed to fire. The concrete is in the former case mostly dry and the duration of the heating is often several days.

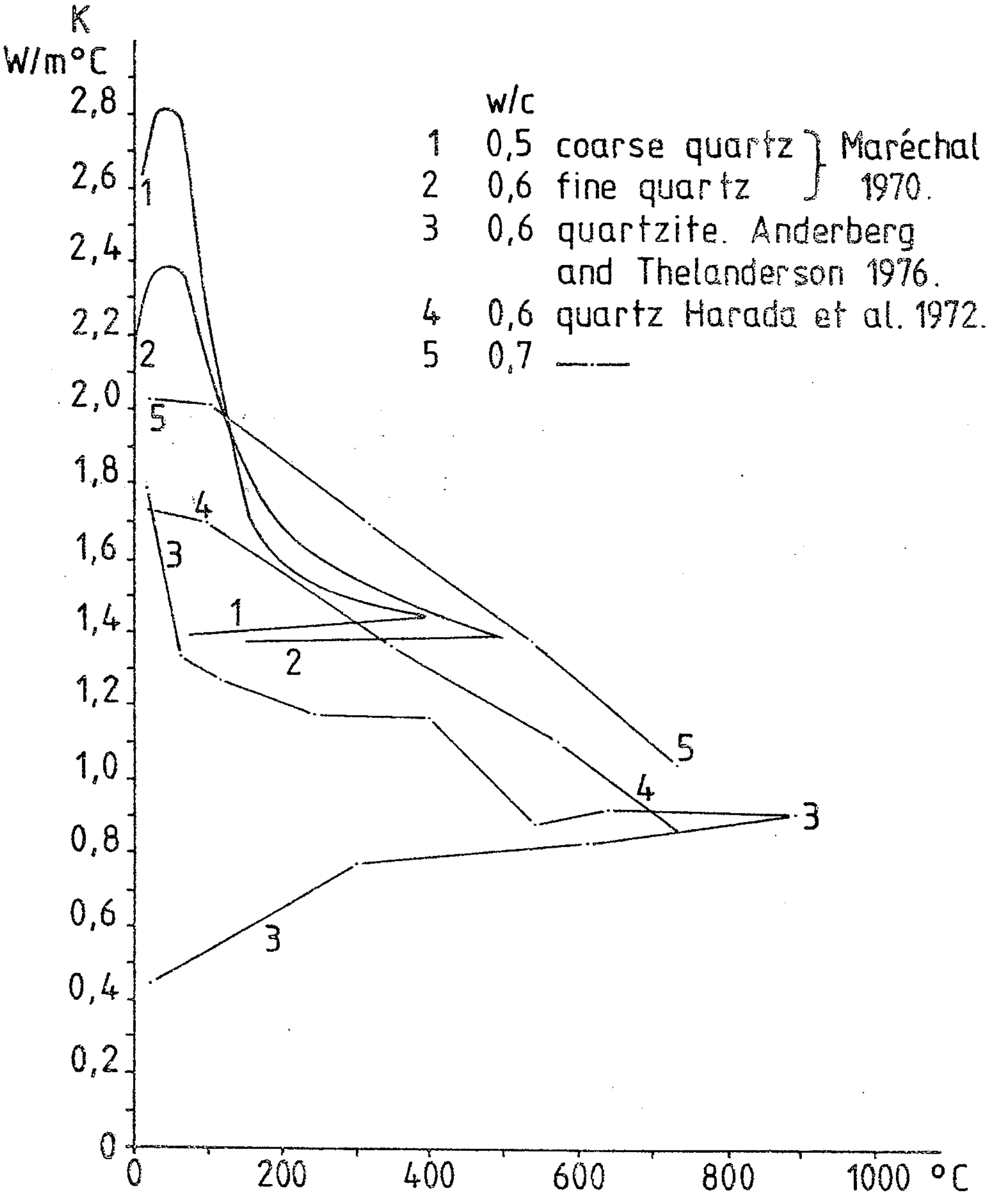
Thus, no matter how careful the conductivity is determined and no matter how precise the tempeature calculation has been executed there will always be an uncertainty of say 40- to 50°C on the temperature distribution in a fire exposed cross section solely arising from uncertainty on the determination of the thermal conductivity.

Some examples of the variation of the thermal conductivity by the temperature are shown on the following pages.

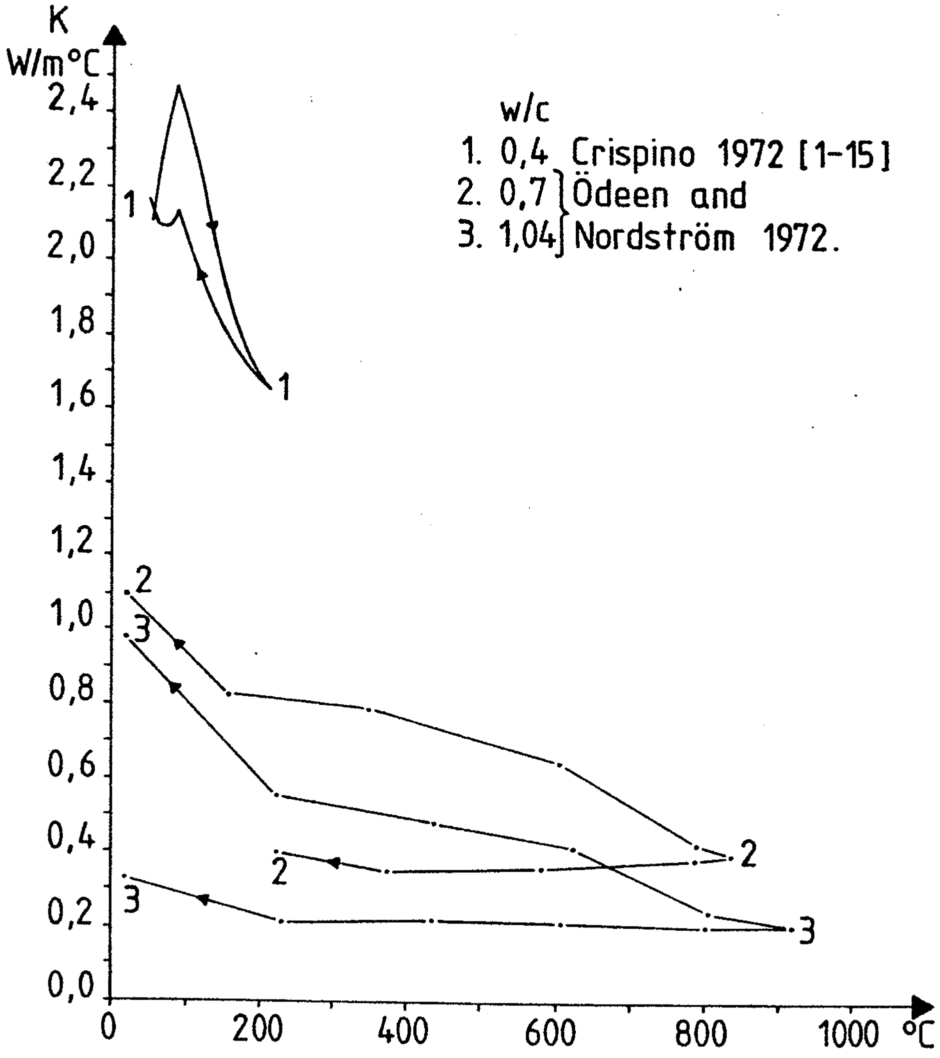
To be noticed is the variation caused by the differences in aggregate and the influence of the heating rate.



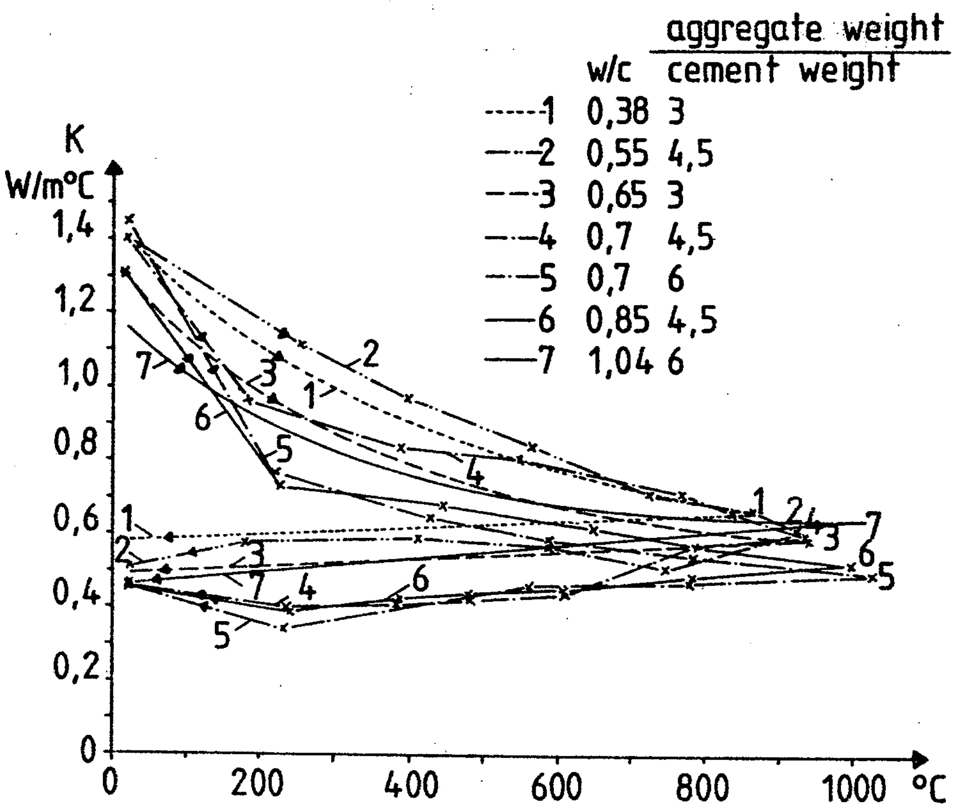
Thermal conductivities for aggregates.



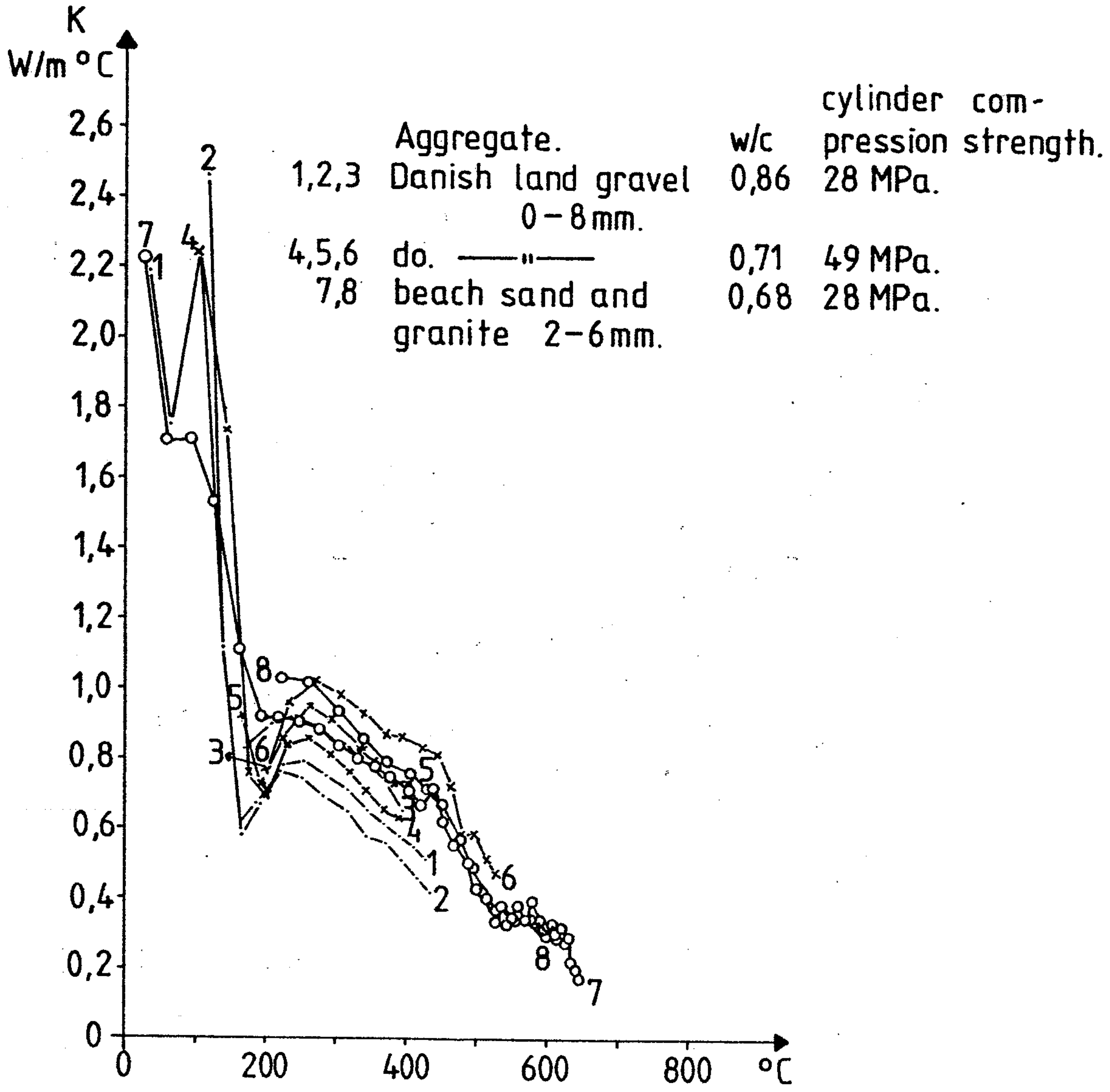
Thermal conductivity for concrete with quartz.



Thermal conductivity for limestone concrete.



Thermal conductivity for granite concrete.
Ödeen and Nordström [18].



Thermal conductivity during a standard fire.
Østergaard 1972 [21].

ON THE SPECIFIC CAPACITY OF HEAT

Unlike the thermal conductivity the specific heat capacity of dry concrete seems to vary only a little with differences in the composition and with the temperature level.

Many authors like Lie [7] and Pettersson and Ödeen [12] propose to use a fixed value of approximately 1.0kJ/kg°C, and the results of the thorough work of Ödeen and Nordström [18] seems to confirm the reasonableness of such an assumption, as the actual value raises only 5- to 10 pct, when the temperature raises from 200°C to 600°C.

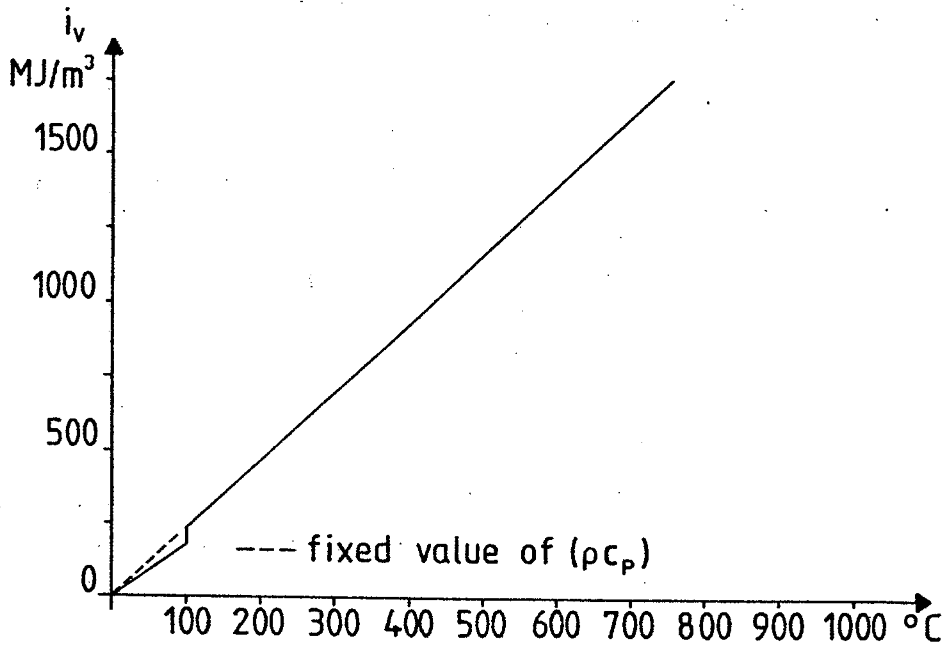
During the experimental investigations the concrete has been examined while cooling and not while heating, which would be more interesting for these applications

Although all processes involved for the dry concrete can not be provided to be reversible at the same temperature levels many authors considers the deviations caused by this to be negligible.

On the other hand one must of course correct for the influence of moisture on the heat demand of the concrete supposed to be heated, especially the local increase of the heat capacity at 100- to 200°C due to evaporation of the free water.

For very precise calculations the moisture can be handled separately taking into account the properties of heat and flow.

1 kg water uses 2.6 MJ while heated from 20- to 100°C and then finally evaporated.



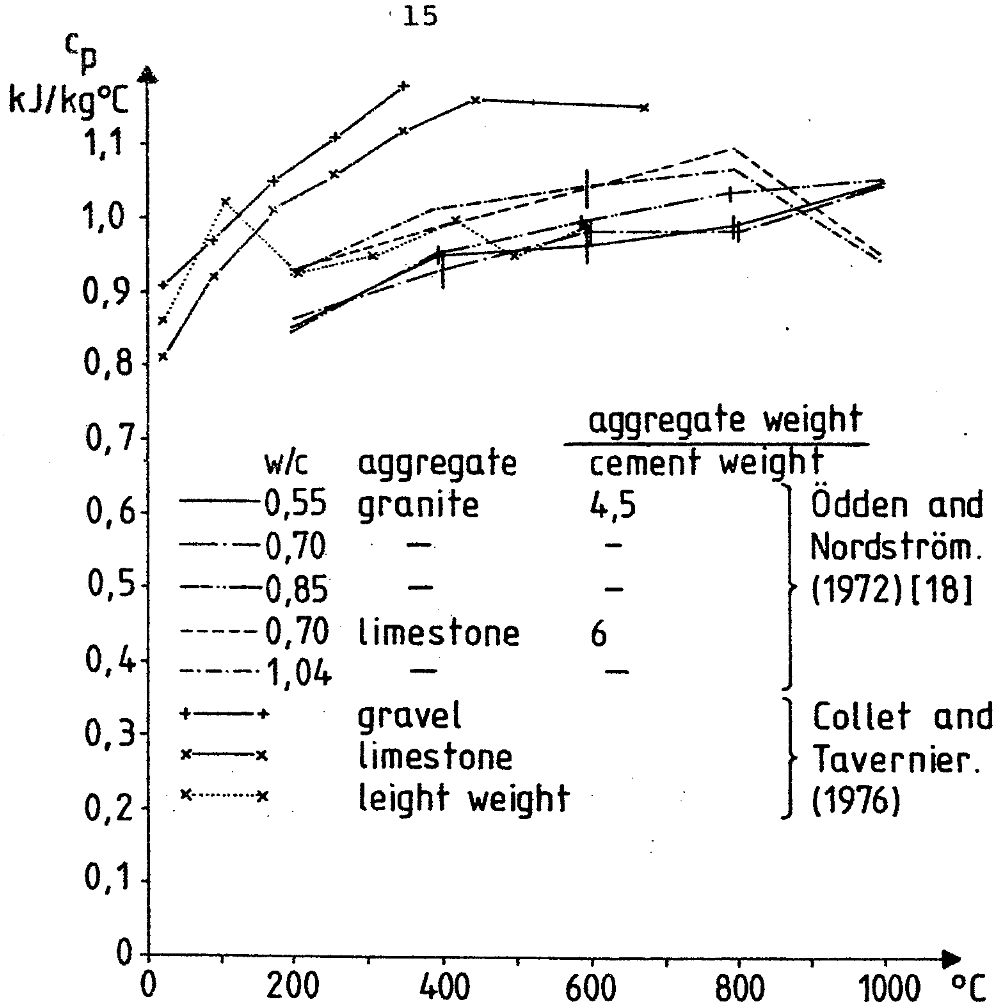
Enthalpy in principle.

The moisture content of structural concrete is ofter about 1- to 3 pct. by weight. That is about 1 pct. for protected structures and 2- to 3 pct. for structures more likely to be exposed to moisture. (See fc example Neville [10] p. 429). A realistic value thus is about 1.5 weight-pct. free water.

While heated to 200°C this moisture uses about 1.5x2 ~ 40 kJ per kg concrete, and related to the total heat demand of the concrete, which is about 200 kJ per kg concrete, this is approximately 20 pct.

An examination of curves showing the development of the specific heat capacity for actual examples of dr concrete indicates that the value is just about 20 p less than 1.0 kJ/kg°C within the first 200°C.

This means that the value 1.0 kJ/kg°C seems to de-



Specific capacities of heat.

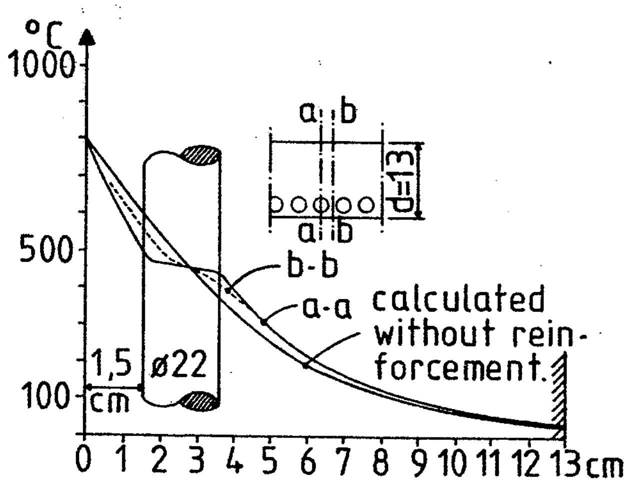
scribe the heat capacity for the total system almost exatly at all temperatures when used in relation to the density of the dry concrete.

Above 200°C the density of the dry concrete decreases slightly.

Using the results from Zoldners [17] the density has decreased 5 pct. at 600°C and thus about the same amount as the slight increase in the specific heat capacity above 200°C. So the product of these two values must be expected to remain almost constant.

This phenomenon facilitates the simple calculations.

CALCULATED TEMPERATURE DISTRIBUTIONS



Temperature distribution in a 13 cm slab
after 1 h standard fire.

A result of major importance to this subject was published by Ehm in 1967, where he showed that if the temperature distribution in a reinforced concret section is calculated as if the section consists of plain concrete, the temperatures at the positions of the centres of the reinforcement bars will be the same as the temperatures of the bars in the corresponding reinforced cross section.

Becker et al. [1] showed that this is a reasonable procedure up to an area of reinforcement of 4% of th total cross sectional area.

In most cases the problem therefore is reduced to th calculation of the temperature distribution in a pla concrete section.

If the effect of evaporation and moisture flow is neglected the heat transport is ruled by the differential equation - Fourier's law:

$$\frac{\partial i_v}{\partial t} = \nabla(K\nabla T)$$

where i_v is the enthalpy (J/m^3), t is the time (s), T is the temperature (for example $^{\circ}$C) and K is the thermal conductivity (W/m$^{\circ}$C).

The corresponding one-dimensional expression is then with fixed conductivity K, specific capacity of heat c_p (J/kg$^{\circ}$C) and density ρ (kg/m^3):

$$\frac{\partial^2 T}{\partial x^2} = \frac{\rho c_p}{K} \frac{\partial T}{\partial t}$$

where x is a simple Euclidean co-ordinate.

Dividing the cross-section into slices of thickness Δx the corresponding difference expression can be solved stepwise graphically or by EDP.

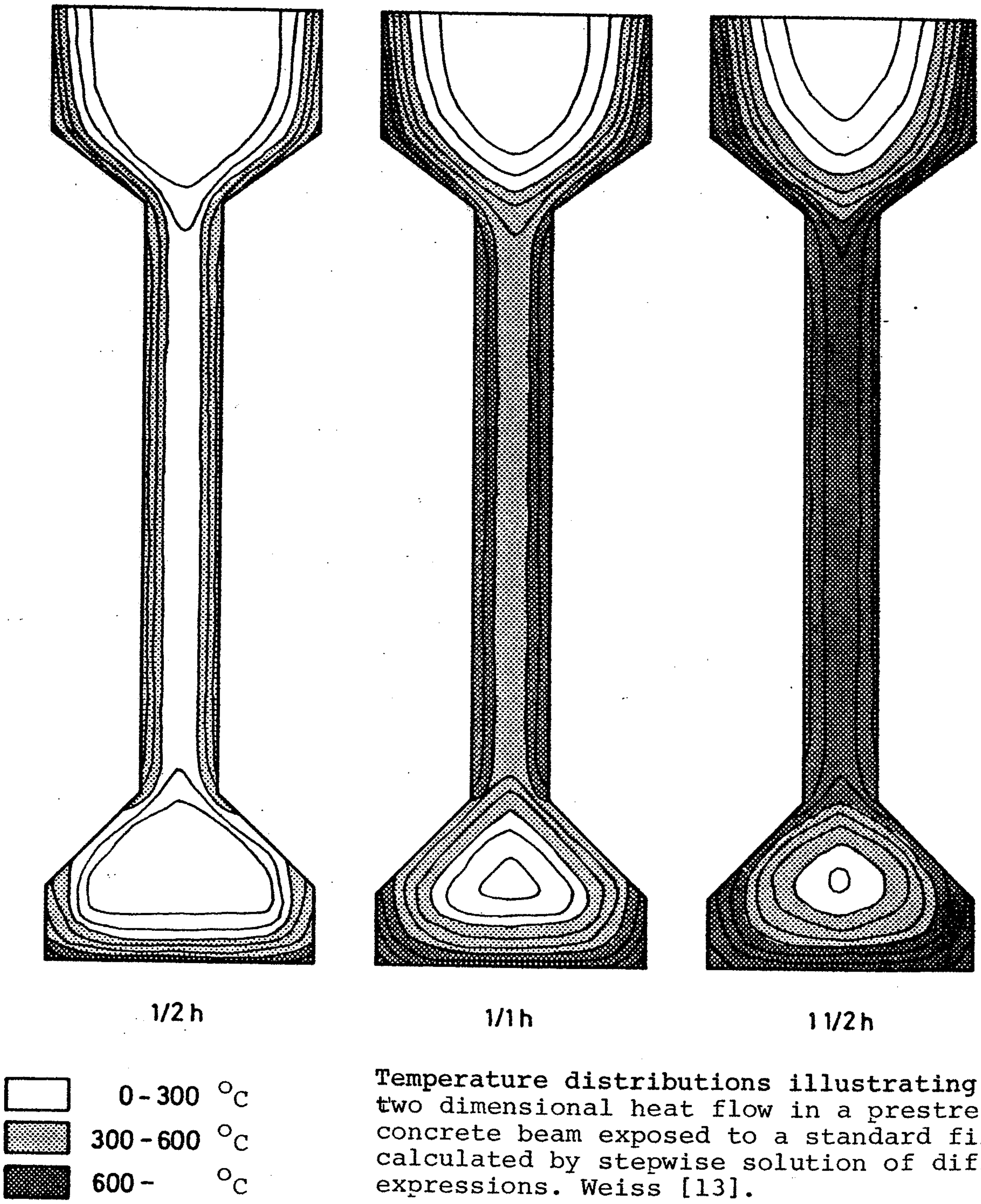
Results of the latter kind are published by for example Ödeen [20], Lie [7] and Maes et al. [8].

Also for two-dimensional heat flow difference expressions are developed and stepwise solutions have been found.

Such solutions are available in for example Ödeen [19], Weiss [13] and Pettersson and Ödeen [12].

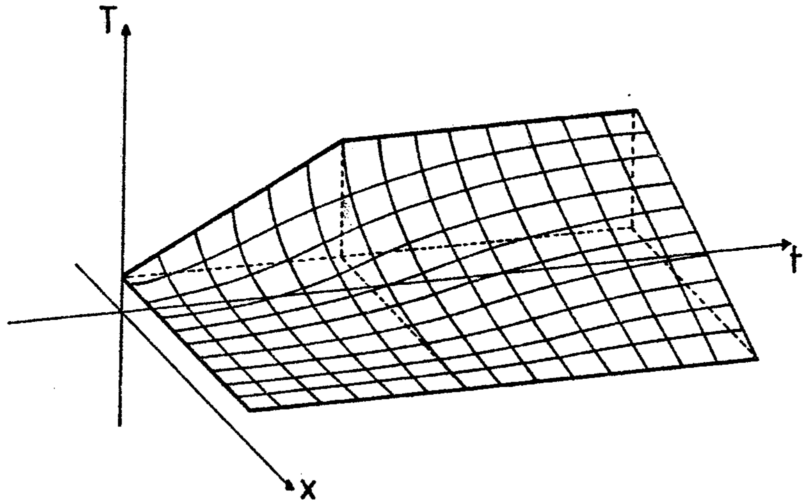
Also the finite element method is applicable to the problem using an appropriate principle of variation.

See for example Zienkiewicz [16], Becker, Bizri and Bresler [1] and Wickström [14] and [15]



Temperature distributions illustrating two dimensional heat flow in a prestressed concrete beam exposed to a standard fire calculated by stepwise solution of difference expressions. Weiss [13].

SOME SIMPLE EXACT SOLUTIONS



Example of an integral surface.

An exact solution to the one-dimensional case obeys the equation

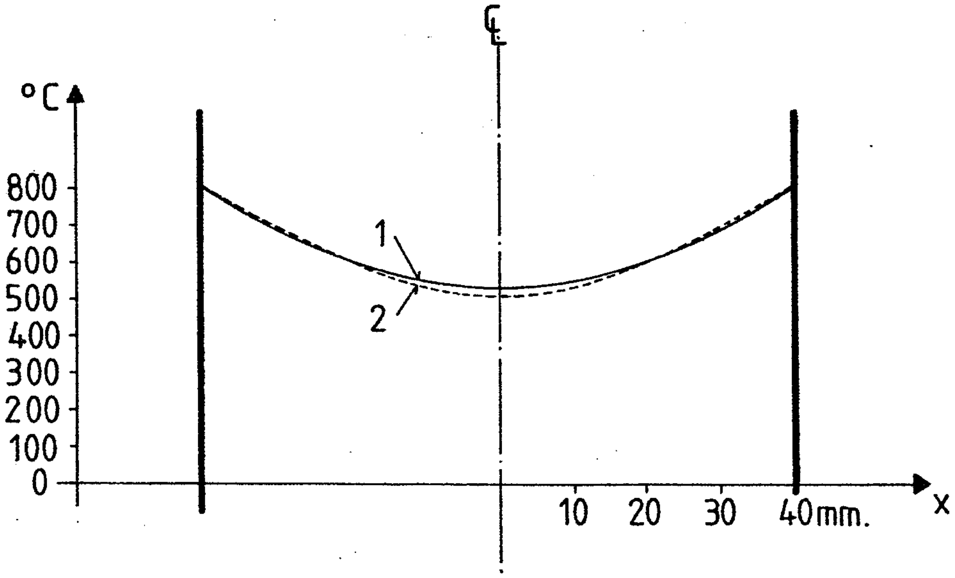
$$\frac{\partial T}{\partial t} = a \frac{\partial^2 T}{\partial x^2}$$

where a is the thermal diffusivity

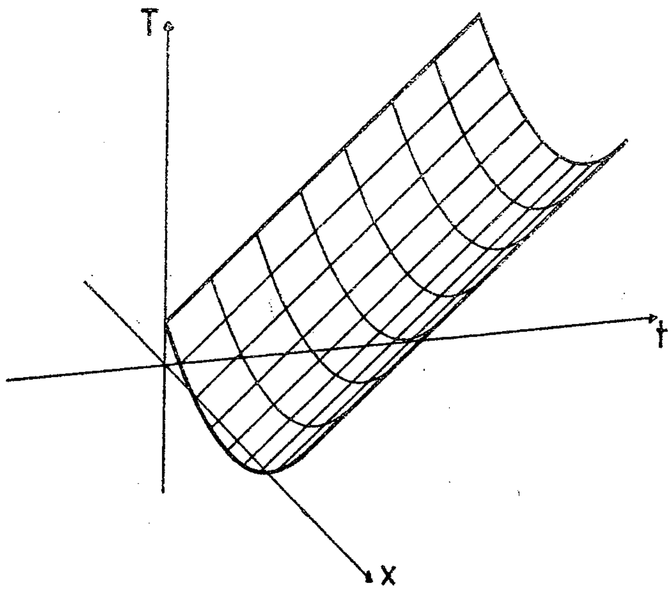
$$a = \frac{K}{\rho c_p}$$

In a x-t-T co-ordinate system such a solution will form a surface.

The inclination of the surface in the t-direction is at every point proportional to the derivative of the second order of the height T i.e. the approximate curvature of the x-direction.



Temperature distribution in the web of a prestressed beam after 1 h standard fire. 1) Parabola. 2) EDP calculation from Weiss [13].



Parabolic solution.

A surface of this kind happens to be an adequate conceptual tool for handling thermal problems related to fire exposed cross-sections.

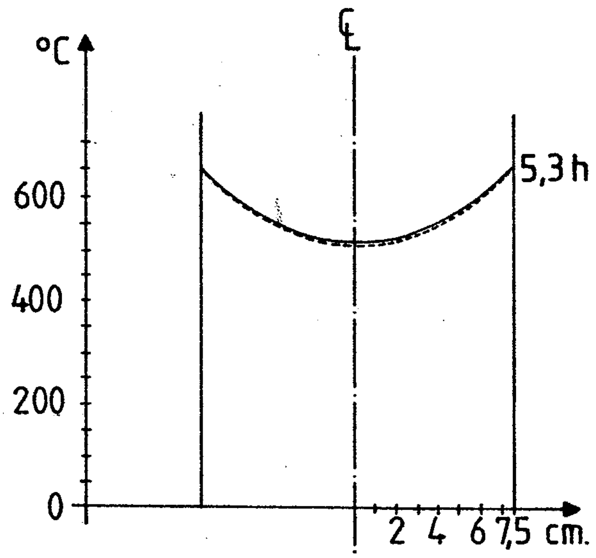
If the surface fulfils the boundary conditions, which for example consist of three boundary curves, it represents the particular integral that forms the exact solution to the problem.

If the temperature at the boundaries raises at constant speed $2aC_1$ for example at two surfaces of a wall exposed from both sides, the parabola of the second degree is an exact solution

$$T = T_o + C_o x + C_1 x^2 + 2aC_1 t$$

where T_o, C_o and C_1 are arbitrary constants.

For a thin wall and a rapid heating this solution



Temperature distribution in a
15 x 30 cm cylinder heated 2^{o}C/min.
——— Paraboloid.
------- EDP calculation.

is often applicable with a sufficient accuracy.

For cylindrical cross-sections the equation of conduction in polar co-ordinates becomes

$$\frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2} = \frac{1}{a}\frac{\partial T}{\partial t}$$

where r is the radius.

Also in this case the parabola of the second degree represents an exact solution

$$T = T_o + Cr^2 + 4aCt$$

Likewise does the parabola of the fourth degree

$$T = T_o + C_1r^2 + 4C_1at + C_2r^2t + \frac{1}{16a}C_2r^4 + 2C_2at^2$$

An exponential solution also exist to the simple plane one-dimensional problem

$$T = T_o + C_ox + C_1e^{(A_1t - \sqrt{\frac{A_1}{a}}x)}$$

where T_o, C_o, C_1 and A_1 are arbitrary constants. Furthermore the damped oscillation known from electromagnetism is an exact solution.

$$T = T_o + C_ox + C_1e^{-\sqrt{v/2a}x}\sin(vt - \sqrt{v/2a}x)$$

where T_o, C_o and C_1 are arbitrary constants and v is the angular velocity.

The surface temperature in this case must vary according to the expression

$$T = T_o + C_1\sin(vt)$$

If the surface temperature at time t = 0 raises to a constant value T_o, a good approximate solution is known as

$$T = T_o\left(1 - \frac{x}{3.363\sqrt{at}}\right)^2$$

Finally a simple exact solution proposed by Joseph Fourier himself in [3] has to be mentioned.

Although it is not incorporated in the procedure presented on the following pages, it may be valuable for rough calculations in fire technology.

In fact it is an exact solution for a rectangular prism with a surface temperature varying exponentially in time.

The exponential decrease in temperature is interesting because it is easily superimposed to describe the variation according to the standard fire curve until the decay period (which unfortunately seldomly is described in the national standards).

As an example the present Danish Standard fire curve is composed by exponential terms.

$$T - T_o = 1325-430e^{-0.2t}-270e^{-1.7t}-625e^{-19t}$$

With the same terminology as used before Fouriers solution for the surface temperature variation

$T = C\ e^{-mt}$ in the three dimensional case i

$$T = C_o e^{-mt} \cos(C_1 x)\cos(C_2 y)\cos(C_3 z)$$

where x, y and z are coordinates originating at the centre of the prism, and C_o, C_1, C_2 and C_3 are constants obeying the relation

$$m = a(C_1^2 + C_2^2 + C_3^2)$$

and demands concerning the values of the product of cosine functions at the surfaces of the prism.

Two- and one dimensional solutions are naturally for by introducing $C_3 = 0$ and $C_2 = 0$ respectively.

PRACTICAL APPROACH

The simple exact solutions mentioned in the previous chapter would be of limited interest if it was not for the fact that the equation of conduction allows superposition. That is, two exact solutions can be multiplied by constants and added, and the result is still an exact solution.

By means of this procedure many realistic boundary conditions can be fulfiled almost exactly.

In spite of the fact, that an uncertainty of about 50°C has to be accepted exclusively according to the difficulties in the assessment of the thermal conductivity, the author finds it convenient to use a simple procedure for the temperature calculation giving rise to uncertainties of about 30-40°C.

The procedure proposed in this presentation approximates the surface temperature development of a fire exposed construction with an arbitrary rectangular cross-section to an idealized development that is achieved by superposition of solutions to the equation of conduction.

The surface temperature development is composed by three elementary developments representing three basic solutions. These are a fixed temperature superimposed by a harmonic oscillation and after a half period superimposed by an exponential solution in the cooling phase.

By means of these three simple elements every fire development can be simulated with a sufficient accuracy.

In this context the fire developments of interest are chiefly the standard fire defined by for example ISO 834, succeeded by realistic cooling sequences, or actual fire developments specified by the fire loads and the opening factors according to Magnusson and Thelandersson [9].

The simulated solution to the plane one-dimensional problem can be written as

$$T(x,t) = f_1(x,t) + f_2(x,t) + f_3(x,t)$$

where

$$f_1(x,t) = E'\left(1 - \frac{x}{3.363\sqrt{at}}\right)^2$$

for $\left(1 - \frac{x}{3.363\sqrt{at}}\right) > 0$, else $f_1(x,t) = 0$

and E' is the constant temperature.

$$f_2(x,t) = D'e^{-\sqrt{v/2a}x}\sin(vt-\sqrt{v/2a}x)$$

for $(vt-\sqrt{v/2a}x) > 0$, else $f_2(x,t) = 0$

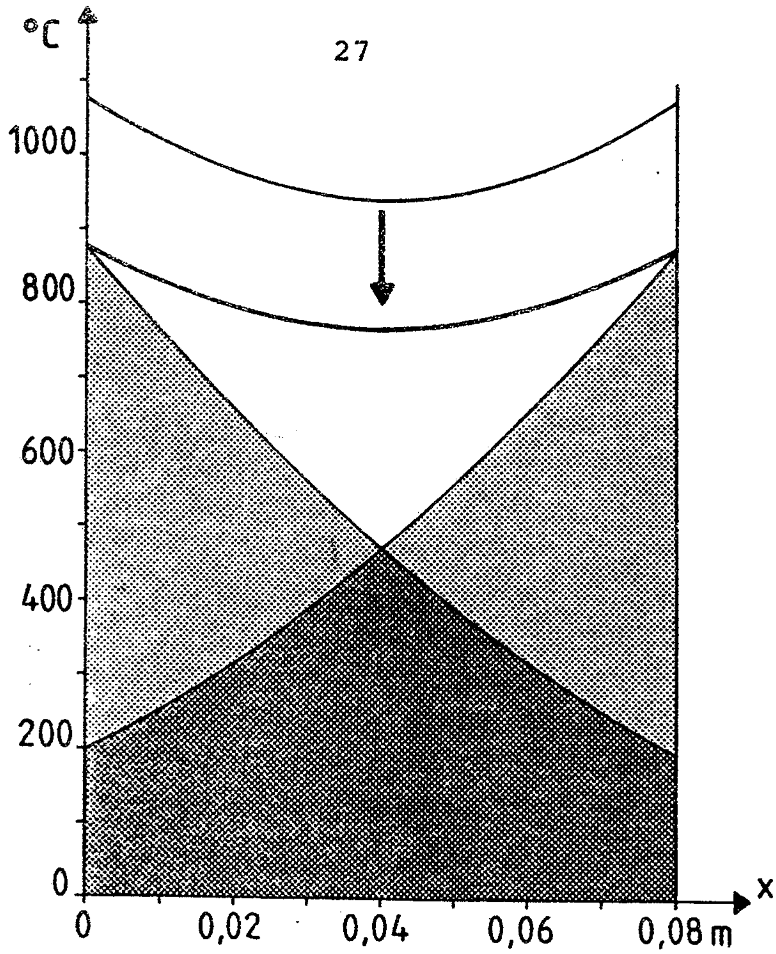
where D' is the amplitude of the harmonic oscillatic at the surface, and with the half period called C', the angular velocity will be $v = \pi/C'$.

$$f_3(x,t) = \frac{D' + E'}{2(e^{LC'}-1)}\left(1 - e^{(L(t-C')-\sqrt{L/a}x)}\right)$$

for $(L(t-C')-\sqrt{L/a}x) > 0$, else $f_3(x,t) = 0$

where $L = \frac{2}{C'} \ln \frac{3D'}{E'-2D'}$.

L defines the shape of the temperature curve in the cooling sequence being assessed by the surface temperatures:



Temperature distributions from two sides.

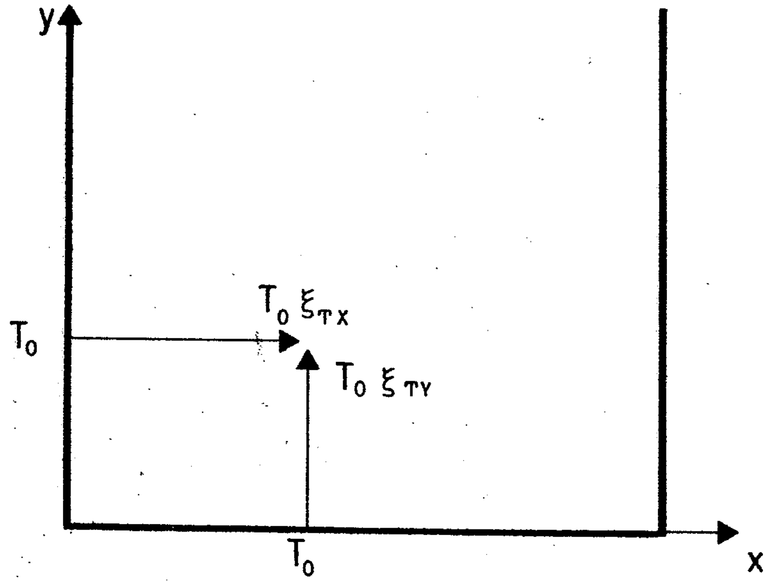
$$T(0,C') = E'$$

$$T(0,\tfrac{2}{3}C') = \frac{E'}{2}$$

$$T(0,2C') = \frac{E'-D'}{2} .$$

For constructions simultaneously exposed to fire at two parallel surfaces, as for example walls and compression zones in top of beams, a one-dimensional solution from the one side is superimposed by the same solution from the other side, and the new temperature distribution is multiplied by the relation between the surface temperature wanted and the surface temperature from the added solution.

This simple procedure leads to temperature distributions which are in close accordance with known measured or precisely calculated distributions, as shown by the examples in Appendix A (calculated by Pedersen [11]).



Temperature reduction in a section exposed on three sides.

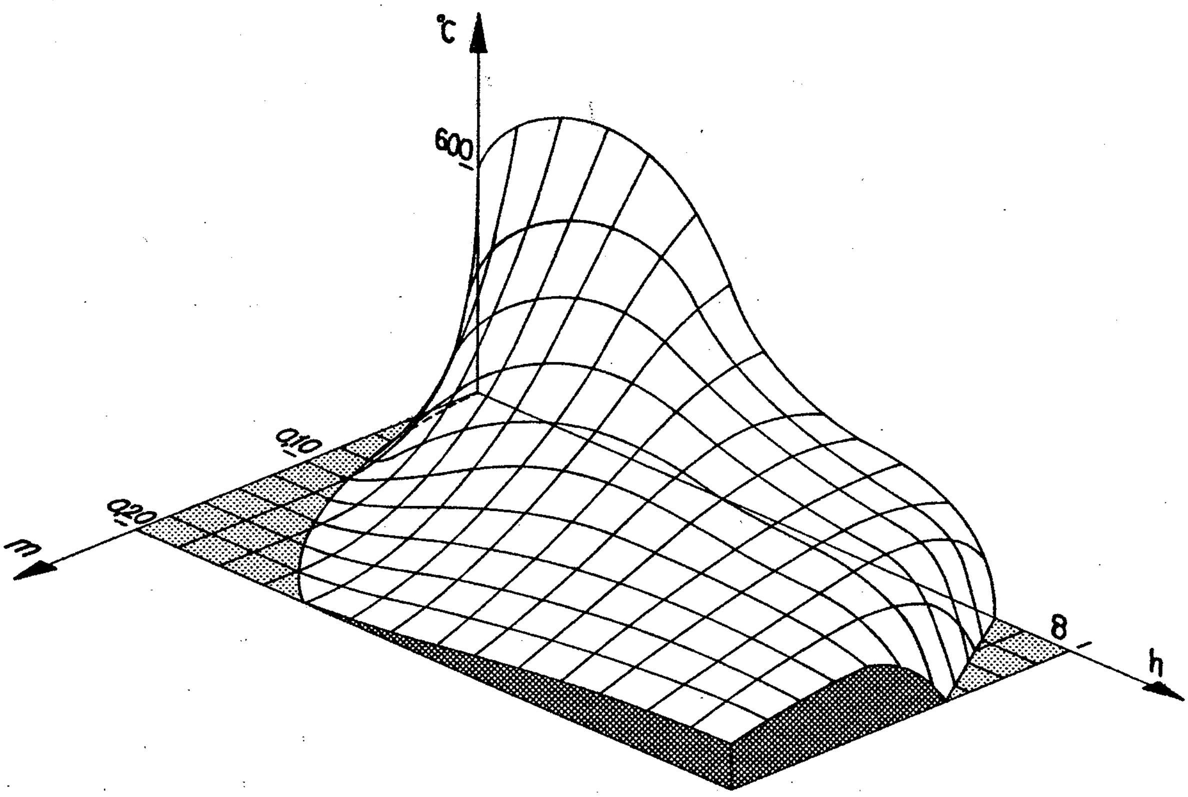
Analysing fire exposed concrete constructions it is often desirable being able to calculate the temperature in a point of a rectangular cross-section expos on the three sides.

Unlike the procedures dealt with on the previous pag a well known method is available for the simple calculation (for example Carslaw and Jaeger [2]).

If the reduction factor of the temperature is called ξ_{Tx} in the depth x of a section exposed at two sides and ξ_{Ty} in the depth y of a section exposed at one side, the temperature in the point (x,y) of the section exposed at three sides is calculated approximat as

$$T(x,y) = T_o(\xi_{Tx} + \xi_{Ty} - \xi_{tx}\xi_{Ty})$$

where T_o is the surface temperature.



Integral surface for the simple calculation procedure.

The author has developed a program for the simple calculation of temperatures in a cross-section exposed by fire at one-, two- or three surfaces by means of an advanced pocket calculator.

The program is listed in Appendix C, where also the documentation necessary for operating the program can be found.

Examples of temperature calculations of cross-sections exposed on three sides are shown in Appendix B (calculated by Pedersen [11]).

It will be seen, that the simple calculation in this case leads to temperatures which are somewhat too high especially in the vicinity of a corner.

The increment of the temperatures in these zones of the cross-section is advantageous because it is of the same amount as the increment caused by the bevelled edges, that often are found on fire exposed rectangular construction elements as a result of the spalling effect.

This effect is caused by the flow of steam from the cross-section giving rise to an explosive destruction of the surface especially at convex corners where the thermal stresses are contributory to the phenomenon.

Because it happens at an early stage of the fire it causes certain changes of the isotherms of the cross section during the largest part of the fire development.

APPLICATIONS FOR THE SIMPLE CALCULATION PROCEDURE

It is obvious that a quick estimation of the temperature to a certain time at a point of a cross-section exposed to a certain fire is advantageous in relation to fire technological research.

The consulting engineer also has a need of such a procedure while selecting various sorts of fire precautions or designing a concrete construction for fire resistance.

In this case especially the temperatures of the reinforcement bars are of interest, and the problem is characterized by the fact that they are located at single points of the cross-section.

Many of the fire technological phenomena of relevance for the designing process are far from simultaneous.

The time at which the maximum temperature occurs during a fire is highly dependent on the position of the point considered in the cross-section.

It is therefore important being able to maximize the temperature or temperature dependent phenomena at a reasonable speed and cost.

The procedure proposed is advantageous because it allows a mathematical treatment of many of these maximizations, or it simply offers a fast working subroutine for the temperature calculation as a part of a larger calculation.

The procedure is shown in Appendix D where it is translated into PL/1 (Programming Language One) for application in an EDP program.

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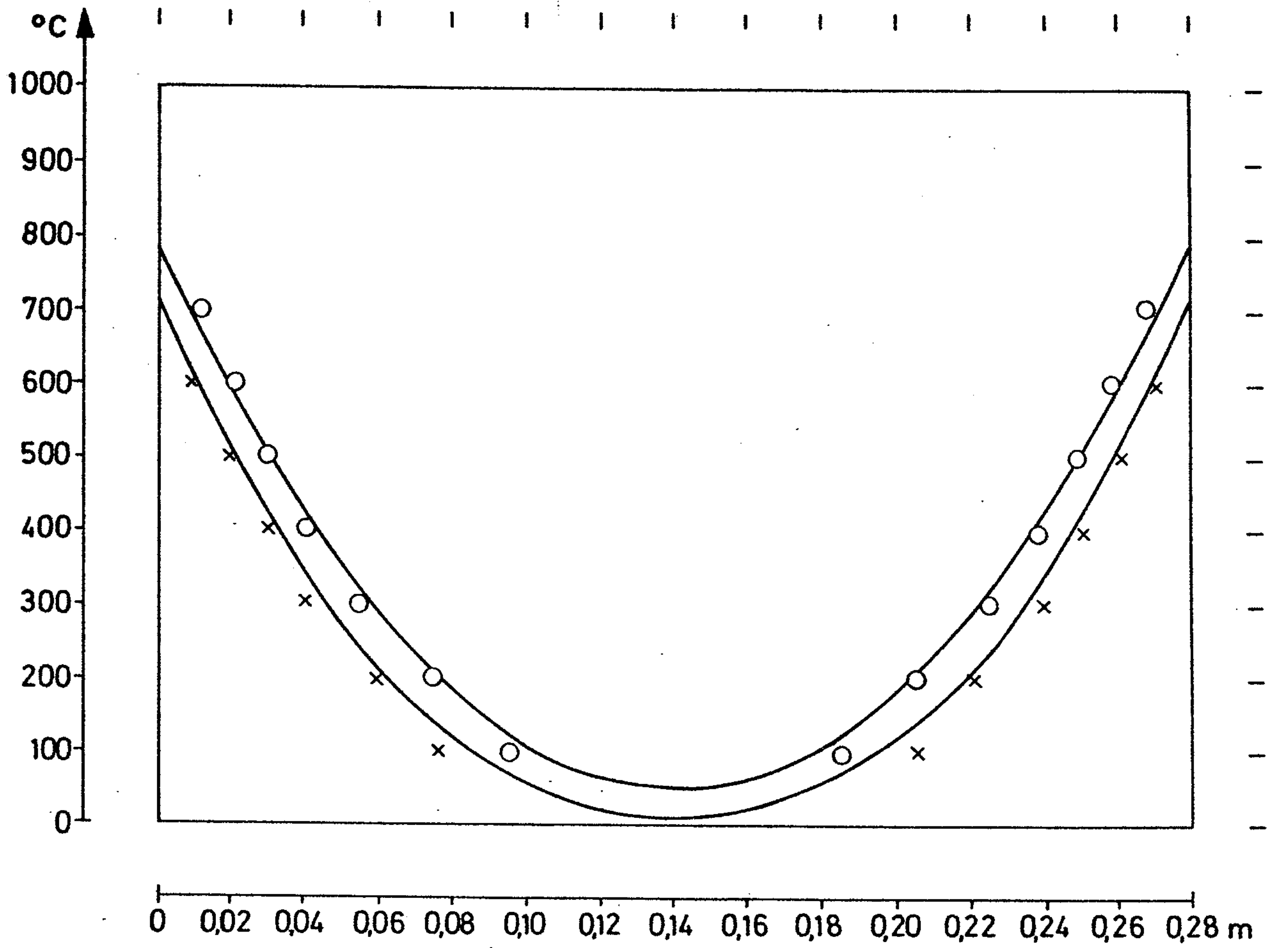
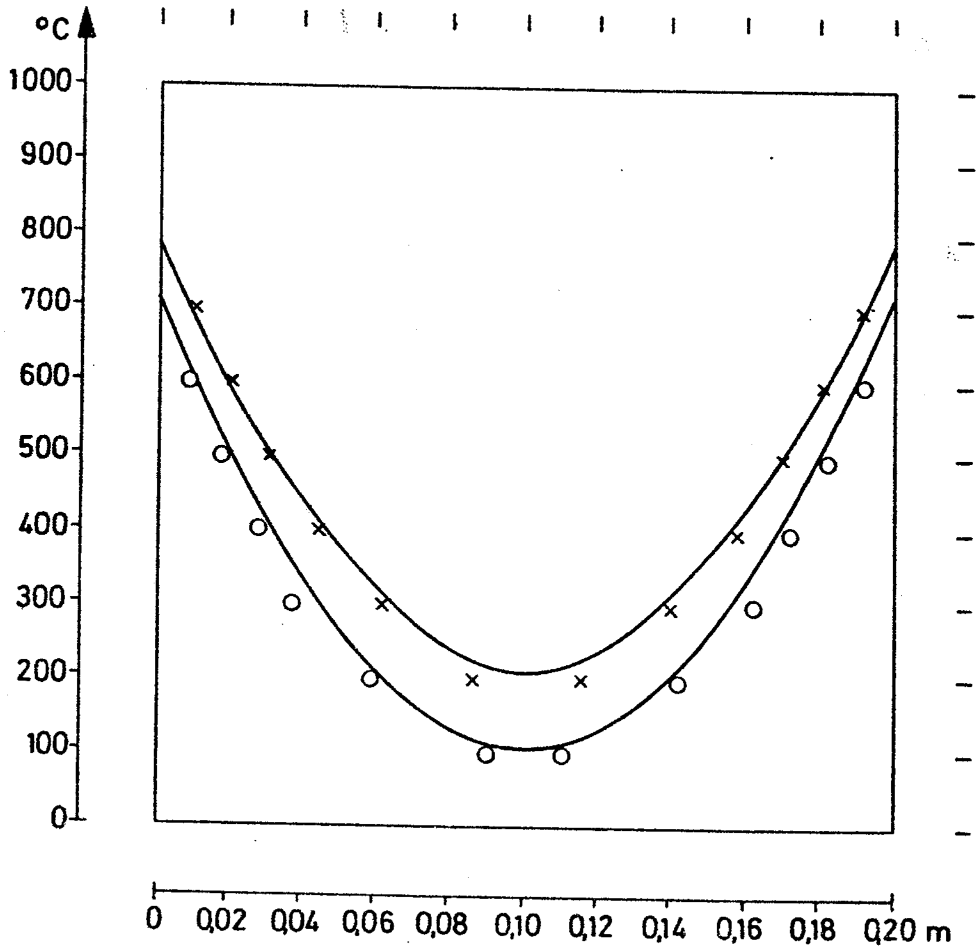
Instituttet for Husbygning, DTH.
Lyngby 1972.

APPENDIX A



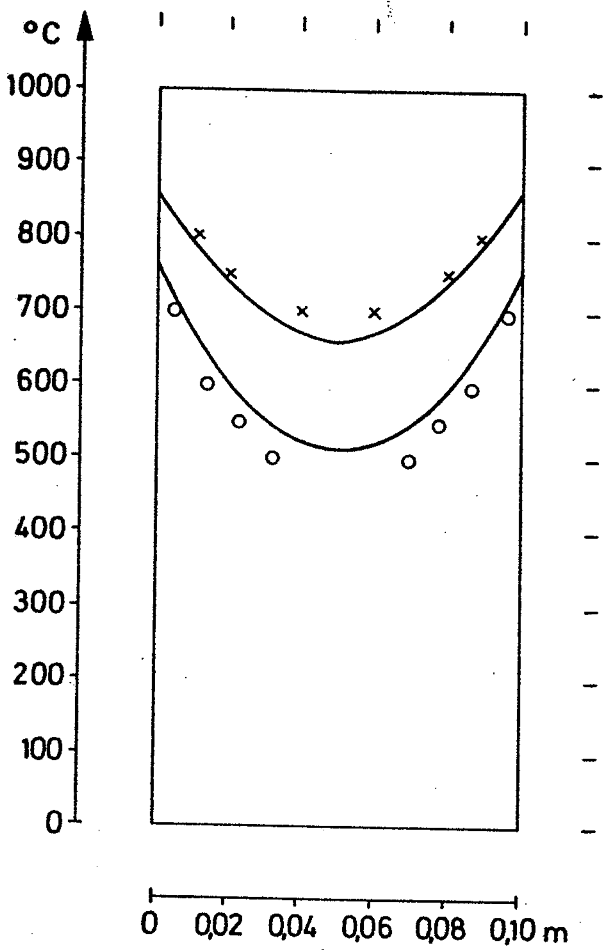
Temperature distribution calculated by the program Incendioret after 1.0 and 1.5 h standard fire. The points indicated are measured temperatures (Kordina et al. [6]).

APPENDIX A



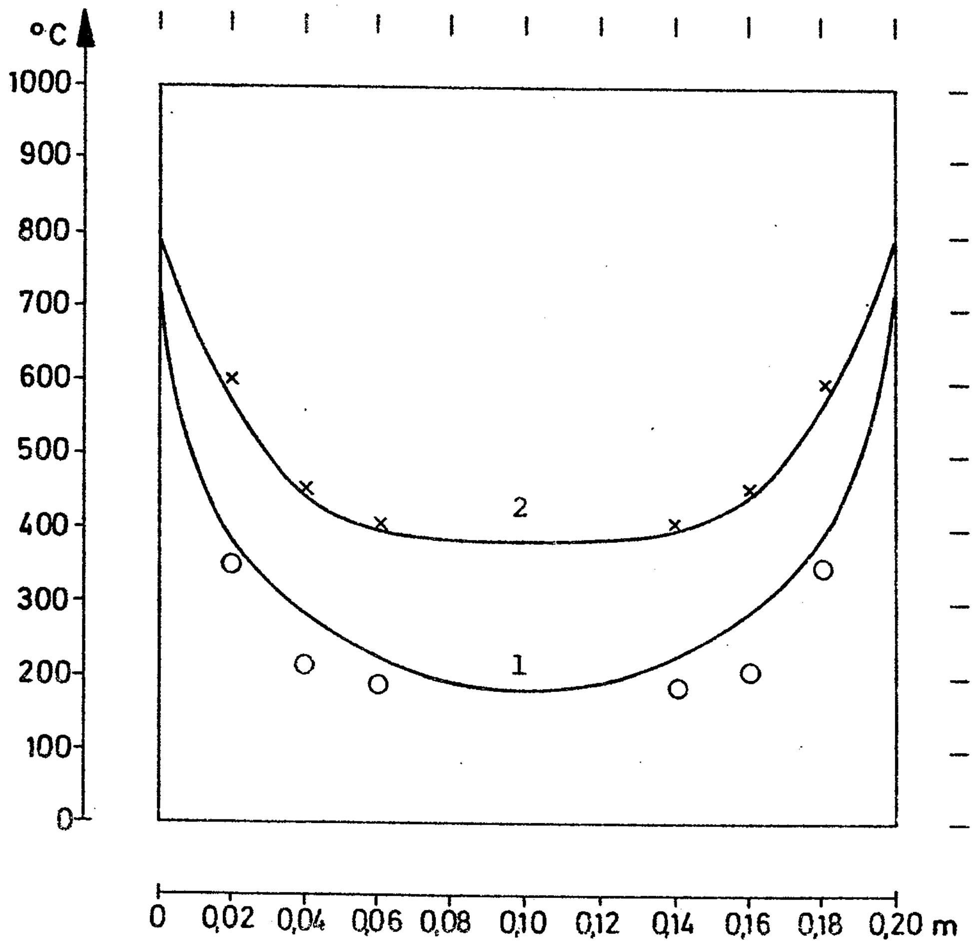
Temperature distribution calculated by the program Incendioret after 1.0 and 1.5 h standard fire. The points indicated are measured temperatures (Kordina et al. [6]).

APPENDIX A



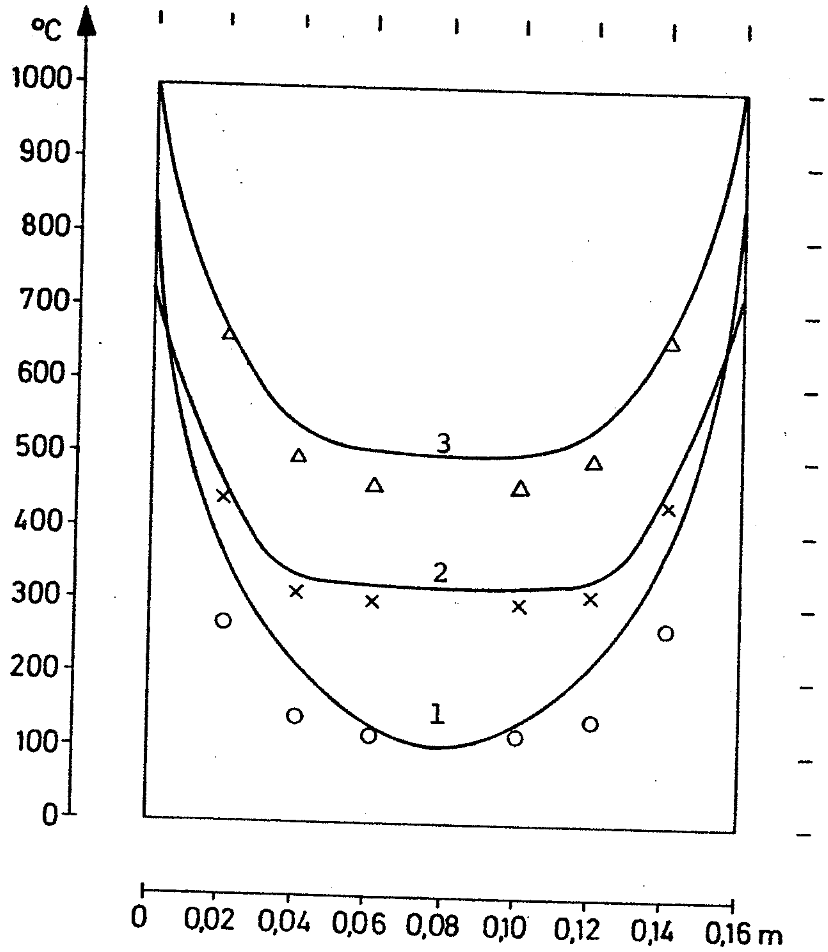
Temperature distribution calculated by the program Incendioret after 1.0 and 1.5 h standard fire. The points indicated are measured temperatures (Kordina et al. [6]).

APPENDIX A



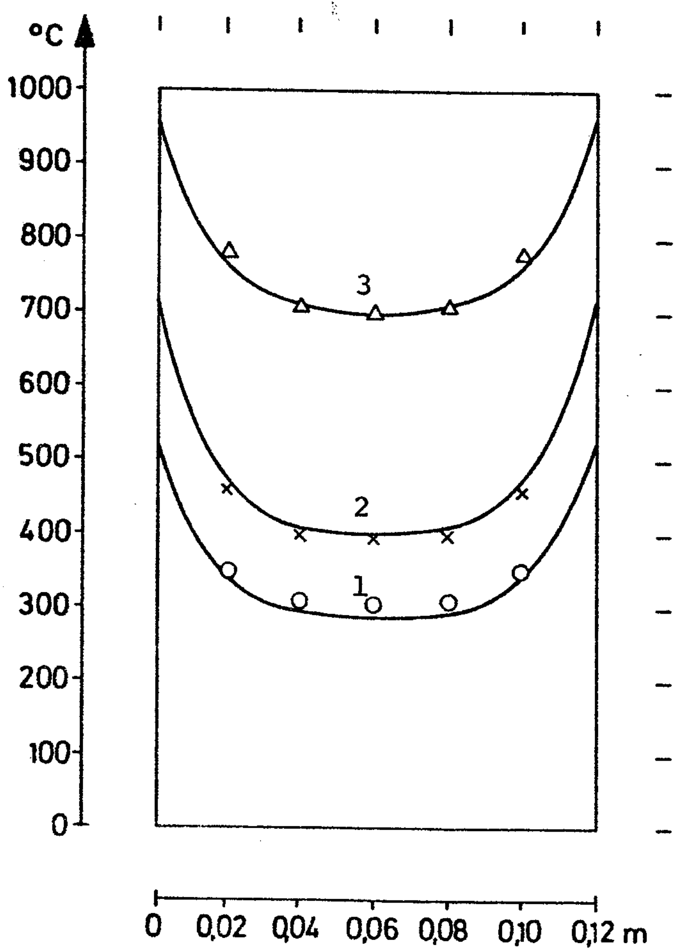
Distribution of maximal temperatures calculated by the program Incendioret at a fire of (opening factor, fire load) =
1: (0.06,150) ($m^{1/2}$,MJ/m^2)
2: (0.04,400) -
The points indicated are temperatures calculated by EDP (Pettersson and Ödeen [12]) (TASEF-2 [15])

APPENDIX A



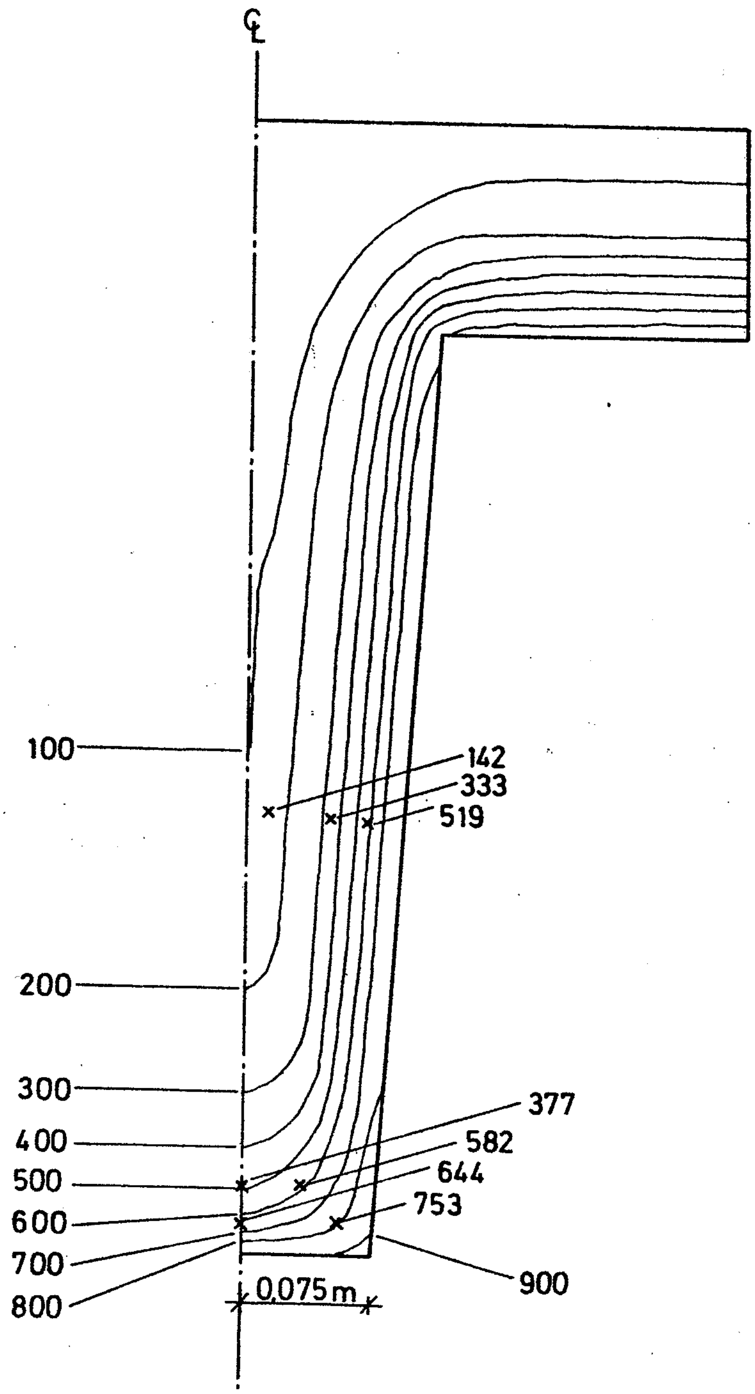
Distribution of maximal temperatures calculated by the program Incendioret at a fire of (opening factor, fire load) =
1: (0.12,150) $(m^{\frac{1}{2}}, MJ/m^2)$
2: (0.04,200) –
3: (0.12,900) –
The points indicated are temperatures calculated by EDP (Pettersson and Ödeen [12]).
(TASEF-2 [15])

APPENDIX A



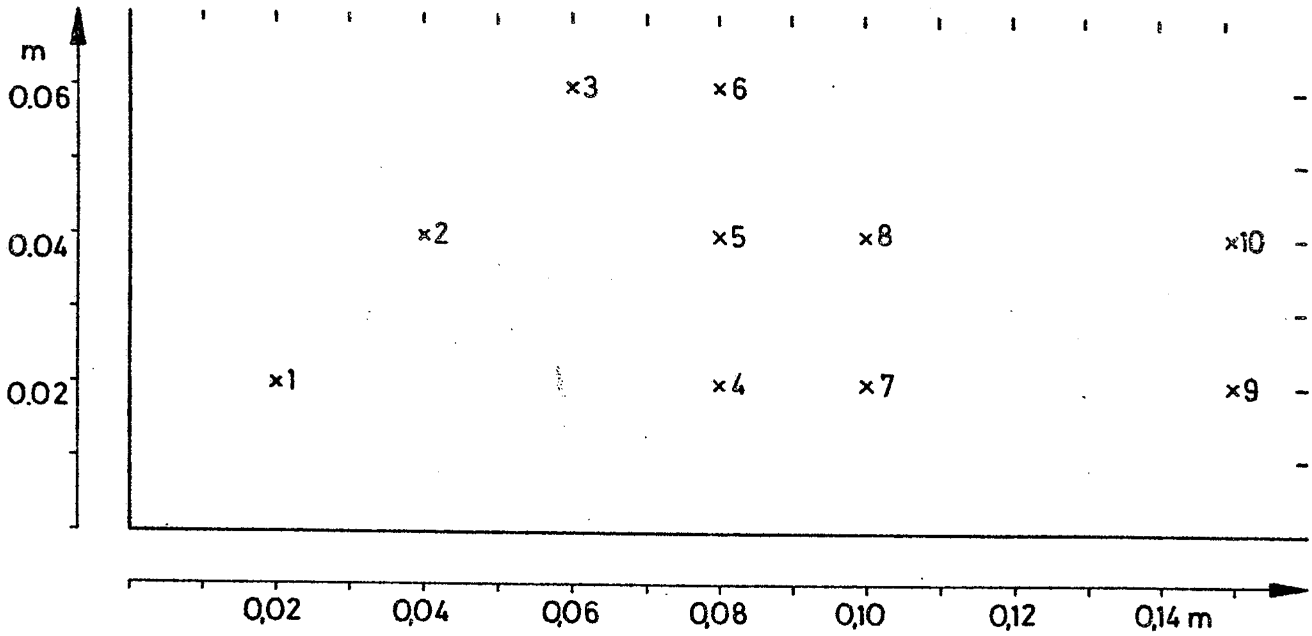
Distribution of maximal temperatures calculated by the program Incendioret at a fire of (opening factor,fire load) =
1: (0.02,100) ($m^{\frac{1}{2}}$,MJ/m^2)
2: (0.04,200) –
3: (0.08,800) –
The points indicated are temperatures calculated by EDP (Pettersson and Ödeen [12]) (TASEF-2 [15])

APPENDIX B



Comparison between temperatures calculated stepwise by means of difference expressions on EDP (Weiss [13]) - the isotherms - and by the program Incendioret - the points - in a beam exposed to 1 h standard fire.

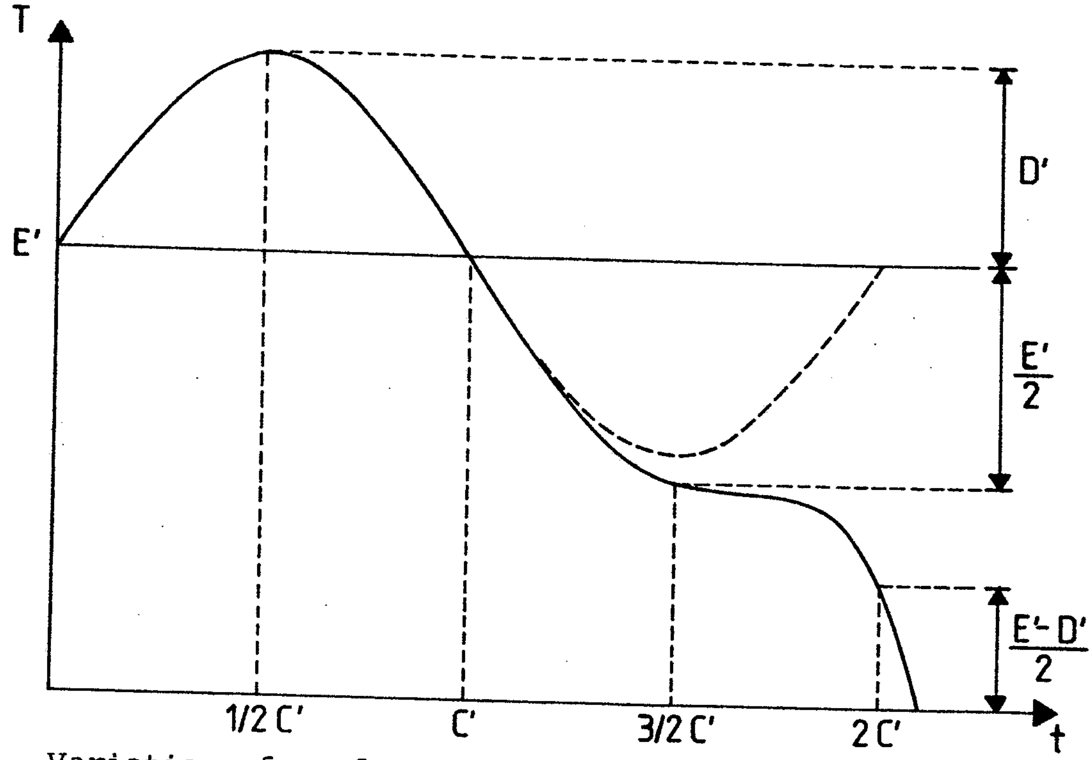
APPENDIX B



Comparison between maximal temperatures calculated by the program Incendioret and by EDP (Pettersson and Ödeen [12]) in a corner of a rectangular beam exposed to fires characterized by opening factor and fire load. (TASEF-2 [15])

(opening factor, fire load) ($m^{½}$, MJ/m^2)	Beam with (m)	Point –	Temperature Incendioret (°C)	Temperature EDP (°C)
(0.04,200)	0.16	1	674	645
		2	490	450
		3	374	375
		4	546	480
		5	425	400
(0.04,300)	0.20	1	740	740
		2	578	550
		3	437	440
		7	590	565
		8	468	455
(0.06,600)	0.16	1	919	895
		2	775	725
		3	674	640
		4	818	760
		5	721	670
		6	662	630
(0.08,600)	0.30	1	900	865
		2	704	625
		3	534	465
		7	716	630
		8	535	445
		9	702	615
		10	505	415

APPENDIX C



Variation of surface temperature for Incendioret.

THE POCKET CALCULATOR PROGRAM INCENDIORET

The pocket calculator program INCENDIORET is listed on the following pages. It is written for the pocket calculator TI Programmable 59 from Texas Instruments.

The program calculates the temperature in a point of a semiinfinite specimen, a slab exposed on two sides (and thus a slab with a perfect insolation on the one side calculated as a two side exposed slab of the double thickness) and a rectangular section exposed on the three sides.

The material is described by a fixed thermal diffusivity and the temperature variation on a surface exposed to the actual fire is described by three constants C', D' and E'.

The program is not able to calculate temperatures after the time of the maximum temperature at the point.

APPENDIX C

OPERATION OF THE PROGRAM INCENDIORET

First the material and the fire is described.

TYPE		PRESS
The thermal diffusivity	(m^2/s)	A'
The half period	(h)	C'
The thermal amplitude	(^oC)	D'
The constant temperature	(^oC)	E'

Then the temperature can be calculated in any point.

TYPE		PRESS
The depth from the surface of a semiinfinite specimen	(m)	A
The time in hour from the start of the fire	(h)	B

This gives the temperature in a semiinfinite specime
If the specimen is a slab exposed on two sides then

TYPE		PRESS
The slab thickness	(m)	C

The display shows the new temperature.
If the temperature in another depth is wanted at the same time then

TYPE		PRESS
The new depth	(m)	D

If the section is rectangular then

TYPE		PRESS
The depth from the third surface	(m)	E

APPENDIX C

INDATA FOR INCENDIORET

The values of D' and E' describe the temperature development at a plane surface absorbing radiant energy from the fire in a hemispherical space such as the surface of a slab or the bottom of a broad beam.

If the angle factor for radiation from the fire to the surface is less than 1.0, the values of D' and E' must be adjusted accordingly.

For web surfaces of beams at the ceiling of the enclosure it is recommended to multiply the values of D' and E' by the factor 0.9. These adjusted values are refered to as D'_{web} and E'_{web}.

STANDARD FIRE

RATING	C'	D'	E'	D'_{web}	E'_{web}
0.5 h	1.0	150	600	135	540
1.0 h	2.0	220	600	195	540
1.5 h	3.0	310	600	280	540
2.0 h	4.0	360	600	325	540
3.0 h	6.0	410	600	370	540
4.0 h	8.0	460	600	410	540

OPENING FACTOR = 0.02 $m^{\frac{1}{2}}$

FIRE LOAD	C'	D'	E'	D'_{web}	E'_{web}
75 MJ/m^2	0.6	100	360	90	330
100 MJ/m^2	1.3	185	390	170	350
150 MJ/m^2	2.2	250	400	225	360
200 MJ/m^2	3.2	310	400	280	360
250 MJ/m^2	3.6	350	400	315	360

APPENDIX C

OPENING FACTOR = 0.04 $m^{\frac{1}{2}}$

FIRE LOAD	C'	D'	E'	D'_{web}	E'_{web}
75 MJ/m^2	0.4	135	470	120	420
100 MJ/m^2	0.7	200	510	180	460
200 MJ/m^2	1.2	200	600	180	540
300 MJ/m^2	1.8	240	600	215	540
400 MJ/m^2	2.8	265	600	240	540
500 MJ/m^2	3.4	300	600	270	540

OPENING FACTOR = 0.06 $m^{\frac{1}{2}}$

FIRE LOAD	C'	D'	E'	D'_{web}	E'_{web}
150 MJ/m^2	0.6	150	645	135	580
300 MJ/m^2	1.2	195	680	175	610
450 MJ/m^2	1.8	265	710	240	640
600 MJ/m^2	2.4	270	745	245	670
750 MJ/m^2	3.2	290	750	260	675

OPENING FACTOR = 0.08 $m^{\frac{1}{2}}$

FIRE LOAD	C'	D'	E'	D'_{web}	E'_{web}
100 MJ/m^2	0.3	145	645	130	580
200 MJ/m^2	0.6	170	700	155	630
400 MJ/m^2	1.2	200	725	180	650
600 MJ/m^2	1.8	265	765	240	690
800 MJ/m^2	2.4	270	800	245	720
1000 MJ/m^2	3.0	290	805	260	725

OPENING FACTOR = 0.12 $m^{\frac{1}{2}}$

FIRE LOAD	C'	D'	E'	D'_{web}	E'_{web}
150 MJ/m^2	0.3	220	710	200	640
300 MJ/m^2	0.5	220	780	200	700
600 MJ/m^2	1.0	250	800	225	720
900 MJ/m^2	1.6	250	835	225	750
1200 MJ/m^2	2.2	255	845	230	760
1500 MJ/m^2	3.0	290	860	260	775

APPENDIX C

The pocket calculator program Incendioret

000	76	LBL
001	16	A'
002	42	STO
003	16	16
004	91	R/S
005	76	LBL
006	18	C'
007	42	STO
008	18	18
009	55	÷
010	89	π
011	95	=
012	35	1/X
013	42	STO
014	21	21
015	55	÷
016	43	RCL
017	16	16
018	55	÷
019	07	7
020	02	2
021	00	0
022	00	0
023	95	=
024	34	√X
025	42	STO
026	22	22
027	91	R/S
028	76	LBL
029	19	D'
030	42	STO
031	19	19
032	91	R/S
033	76	LBL
034	10	E'
035	42	STO
036	10	10
037	75	-
038	02	2
039	65	×
040	43	RCL
041	19	19
042	95	=
043	42	STO
044	23	23
045	75	-
046	00	0
047	93	.
048	00	0
049	02	2
050	95	=
051	77	GE
052	33	X²
053	00	0
054	93	.
055	00	0
056	02	2
057	42	STO
058	23	23
059	76	LBL
060	33	X²
061	43	RCL
062	23	23
063	35	1/X
064	65	×
065	43	RCL
066	19	19
067	65	×
068	03	3
069	95	=
070	23	LNX
071	65	×
072	02	2
073	55	÷
074	43	RCL
075	18	18
076	95	=
077	42	STO
078	28	28
079	55	÷
080	43	RCL
081	16	16
082	55	÷
083	03	3
084	06	6
085	00	0
086	00	0
087	95	=
088	34	√X
089	42	STO
090	29	29
091	43	RCL
092	10	10
093	85	+
094	43	RCL
095	19	19
096	95	=
097	55	÷
098	02	2
099	55	÷
100	53	(
101	53	(
102	43	RCL
103	28	28
104	65	×
105	43	RCL
106	18	18
107	54	)
108	22	INV
109	23	LNX
110	75	-
111	01	1
112	54	)
113	95	=
114	42	STO
115	25	25
116	91	R/S
117	76	LBL
118	11	A
119	42	STO
120	11	11
121	65	×
122	43	RCL
123	22	22
124	95	=
125	94	+/-
126	22	INV
127	23	LNX
128	65	×
129	43	RCL
130	19	19
131	95	=
132	42	STO
133	24	24
134	22	INV
135	71	SBR
136	91	R/S
137	76	LBL
138	12	B
139	42	STO
140	12	12
141	65	×
142	43	RCL
143	21	21
144	75	-
145	43	RCL
146	22	22
147	65	×
148	43	RCL
149	11	11
150	95	=
151	22	INV
152	77	GE
153	88	DMS
154	70	RAD
155	38	SIN
156	65	×
157	43	RCL
158	24	24
159	95	=
160	42	STO
161	26	26
162	61	GTO
163	99	PRT
164	76	LBL
165	88	DMS
166	00	0
167	42	STO
168	26	26
169	76	LBL
170	99	PRT
171	00	0
172	42	STO
173	20	20
174	43	RCL
175	18	18
176	75	-
177	43	RCL
178	12	12
179	95	=
180	65	×

APPENDIX C

181	43	RCL
182	28	28
183	85	+
184	53	(
185	43	RCL
186	29	29
187	65	×
188	43	RCL
189	11	11
190	54	)
191	95	=
192	77	GE
193	66	PAU
194	94	+/-
195	22	INV
196	23	LNX
197	94	+/-
198	85	+
199	01	1
200	95	=
201	65	×
202	43	RCL
203	25	25
204	95	=
205	42	STO
206	20	20
207	76	LBL
208	66	PAU
209	43	RCL
210	20	20
211	85	+
212	53	(
213	53	(
214	53	(
215	53	(
216	53	(
217	43	RCL
218	16	16
219	65	×
220	43	RCL
221	12	12
222	65	×
223	03	3
224	06	6
225	00	0
226	00	0
227	54	)
228	34	√X
229	65	×
230	03	3
231	93	.
232	03	3
233	06	6
234	03	3
235	54	)
236	35	1/X
237	65	×
238	43	RCL
239	11	11
240	94	+/-
241	54	)
242	85	+
243	01	1
244	54	)
245	22	INV
246	77	GE
247	55	÷
248	33	X²
249	65	×
250	43	RCL
251	10	10
252	54	)
253	42	STO
254	27	27
255	61	GTO
256	44	SUM
257	76	LBL
258	55	÷
259	00	0
260	42	STO
261	27	27
262	76	LBL
263	44	SUM
264	43	RCL
265	27	27
266	85	+
267	43	RCL
268	26	26
269	95	=
270	42	STO
271	30	30
272	22	INV
273	71	SBR
274	91	R/S
275	76	LBL
276	13	C
277	42	STO
278	13	13
279	43	RCL
280	30	30
281	42	STO
282	33	33
283	43	RCL
284	11	11
285	42	STO
286	32	32
287	00	0
288	71	SBR
289	11	A
290	43	RCL
291	12	12
292	75	-
293	02	2
294	65	×
295	43	RCL
296	18	18
297	95	=
298	22	INV
299	77	GE
300	98	ADV
301	43	RCL
302	18	18
303	65	×
304	02	2
305	95	=
306	42	STO
307	23	23
308	61	GTO
309	97	DSZ
310	76	LBL
311	98	ADV
312	43	RCL
313	12	12
314	42	STO
315	23	23
316	76	LBL
317	97	DSZ
318	43	RCL
319	23	23
320	71	SBR
321	12	B
322	42	STO
323	34	34
324	43	RCL
325	13	13
326	71	SBR
327	11	A
328	43	RCL
329	12	12
330	71	SBR
331	12	B
332	42	STO
333	35	35
334	67	EQ
335	93	.
336	75	-
337	43	RCL
338	34	34
339	95	=
340	22	INV
341	77	GE
342	93	.
343	43	RCL
344	35	35
345	42	STO
346	34	34
347	76	LBL
348	93	.
349	43	RCL
350	35	35
351	85	+
352	43	RCL
353	34	34
354	95	=
355	35	1/X
356	65	×
357	43	RCL
358	34	34
359	95	=
360	42	STO

APPENDIX C

361	36	36
362	43	RCL
363	32	32
364	94	+/-
365	85	+
366	43	RCL
367	13	13
368	95	=
369	71	SBR
370	11	A
371	43	RCL
372	12	12
373	71	SBR
374	12	B
375	42	STO
376	37	37
377	85	+
378	43	RCL
379	33	33
380	95	=
381	65	×
382	43	RCL
383	36	36
384	95	=
385	42	STO
386	38	38
387	91	R/S
388	76	LBL
389	14	D
390	42	STO
391	40	40
392	71	SBR
393	11	A
394	43	RCL
395	12	12
396	71	SBR
397	12	B
398	42	STO
399	42	42
400	43	RCL
401	40	40
402	94	+/-
403	85	+
404	43	RCL
405	13	13
406	95	=
407	71	SBR
408	11	A
409	43	RCL
410	12	12
411	71	SBR
412	12	B
413	42	STO
414	43	43
415	85	+
416	43	RCL
417	42	42
418	95	=
419	65	×
420	43	RCL
421	36	36
422	95	=
423	42	STO
424	38	38
425	91	R/S
426	76	LBL
427	15	E
428	71	SBR
429	11	A
430	43	RCL
431	12	12
432	71	SBR
433	12	B
434	42	STO
435	39	39
436	65	×
437	53	(
438	01	1
439	75	-
440	53	(
441	43	RCL
442	38	38
443	55	÷
444	43	RCL
445	34	34
446	54	)
447	54	)
448	85	+
449	43	RCL
450	38	38
451	95	=
452	91	R/S
453	00	0

APPENDIX D

PL/1 Subroutine

```
TEMP: PROCEDURE(A3,C3,D3,E3,X3,TI3);
      V = 3.14159265 4/C3;
      ARG2 = E3-2*D3;
      IF ARG2 < 0.02 THEN ARG2 = 0.02;
      ARG = 3*D3/ARG2;
      Z3 = 2*LOG(ARG)/C3;
      ARG1 = SQRT(V/(7200*A3))*X3;
      IF ARG1 = 0 THEN EX = 1;
      ELSE EX = EXP(-ARG1);
      ARG = V*TI3-ARG1;
      IF ARG > 0 THEN
      FU1 = D3*EX*SIN(ARG);
      ELSE FU1 = 0;
      ARG = Z3*(TI3-C3)-SQRT(Z3/(3600*A3))*X3;
      IF ARG > 0 THEN
      FU2 = (D3+E3)*(1-EXP(ARG))/(2*(EXP(Z3*C3)-1));
      ELSE FU2 = 0;
      ARG = 1-X3/(3.363*SQRT(A3*3600*TI3));
      IF ARG > 0 THEN
      FU3 = E3*ARG**2+FU2;
      ELSE FU3 = 0;
      RETURN(FU1+FU3);
      END TEMP;
```